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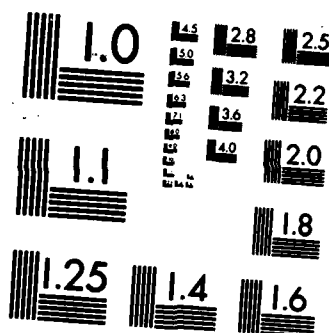
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Annual Technical Report on Grant No.

AFOSR -83-0030

"Amphoteric Impurities in Gallium Arsenide"

Prepared for

AFOSR-TR- 86-0944

UNITED STATES AIR FORCE

OFFICE OF SCIENTIFIC RESEARCH

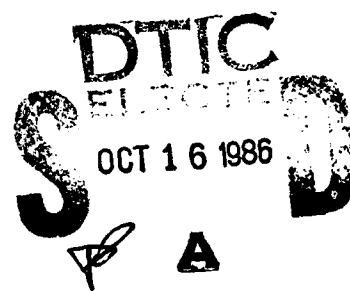
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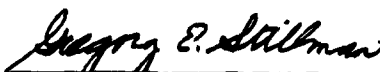
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Principal Investigator

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SECURITY CLASSIFICATION OF THIS PAGE

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS													
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.													
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE																
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 86 - 0944													
6a. NAME OF PERFORMING ORGANIZATION University of Illinois at Urbana-Champaign		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research													
6c. ADDRESS (City, State and ZIP Code) Urbana, Illinois 61801			7b. ADDRESS (City, State and ZIP Code) Bolling AFB, DC 20332-6448													
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR		8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-83-0030													
8c. ADDRESS (City, State and ZIP Code) Bolling AFB, DC 20332-6448			10. SOURCE OF FUNDING NOS. <table border="1"><thead><tr><th>PROGRAM ELEMENT NO.</th><th>PROJECT NO.</th><th>TASK NO.</th><th>WORK UNIT NO.</th></tr></thead><tbody><tr><td>61102F</td><td>2306</td><td>B1</td><td></td></tr></tbody></table>		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.	61102F	2306	B1					
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61102F	2306	B1														
11. TITLE (Include Security Classification) AMPHOTERIC IMPURITIES IN GALLIUM ARSENIDE																
12. PERSONAL AUTHOR(S) Dr. Gregory E. Stillman																
13a. TYPE OF REPORT Annual		13b. TIME COVERED FROM 01 FEB 85 TO 31 JAN 86	14. DATE OF REPORT (Yr., Mo., Day) 1986, July, 14	15. PAGE COUNT 22												
16. SUPPLEMENTARY NOTATION																
17. COSATI CODES <table border="1"><thead><tr><th>FIELD</th><th>GROUP</th><th>SUB. GR.</th></tr></thead><tbody><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr></tbody></table>			FIELD	GROUP	SUB. GR.										18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) <p>Low temperature photoluminescence spectroscopy has been applied to the study of high purity GaAs grown by liquid phase epitaxial, hydride vapor phase epitaxial, metalorganic chemical vapor deposition and molecular beam epitaxial growth techniques. This analytical technique has been used in combination with the analysis of variable temperature Hall effect data to quantitatively analyze the acceptor species present in high purity epitaxial GaAs. The incorporation of the amphoteric column IV elements has been studied for different growth conditions in each of the epitaxial growth techniques.</p>																
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS <input type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED													
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Gerald L. Witt		22b. TELEPHONE NUMBER (Include Area Code) (202) 767-4931	22c. OFFICE SYMBOL NE													

Annual Technical Report on Grant No.

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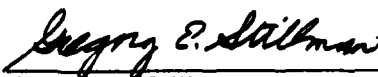
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Principal Investigator

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1. INTRODUCTION

While compound semiconductor materials such as GaAs and InP offer numerous potential advantages over Si in the fabrication of microwave and optoelectronic devices and high speed digital circuitry, their materials and processing technology still lags considerably behind that of Si. One important aspect of materials technology in which this disparity is particularly apparent is the growth of high purity material. The latter is essential in a number of device applications. Large depletion widths are required for efficient light absorption in pin photodetectors, and low doping levels are therefore required. High resistivity buffer layers in microwave or high-speed digital circuits require net doping levels smaller than the trap concentrations in order to be semi-insulating; alternatively, the doping must at least be low enough that the layer is entirely depleted. Gunn effect devices used as microwave amplifiers or oscillators also require low doped material to avoid excessive power dissipation and localized impact ionization at the high fields which are required. Particularly low doping levels are required for stable operation as amplifiers, since the product of carrier concentration and length must be less than 10^{12} cm^{-2} in GaAs to achieve operation in the appropriate mode.¹ Finally, high purity material is invaluable in fundamental materials characterization studies.

Bulk single crystals of Si have been prepared using multiple-pass float-zone refining with residual acceptor (B) and donor (P) concentrations as low as 1.3×10^{11} and $6 \times 10^{10} \text{ cm}^{-3}$, respectively.² Detector-grade Si with [B] as low as $5\text{-}6 \times 10^{11} \text{ cm}^{-3}$ is used commercially by companies such as Hughes and Rockwell. The best bulk GaAs crystals, on the other hand, typically contain at least a few $\times 10^{15} \text{ cm}^{-3}$ of residual acceptors, donors, and stoichiometric defects,³ although they can be produced in semi-insulating form at these doping levels. Bulk InP single crystals have so far been refined only down to a level of $N_A + N_D \approx 10^{15} \text{ cm}^{-3}$; ⁴ this purity level is still several orders of magnitude worse

than for Si. The highest purity epitaxial GaAs is inevitably compensated, and typically has $N_A + N_D$ on the order of 10^{14} cm^{-3} .⁵ Epitaxial InP is less pure.⁵ Identification and elimination of the residual impurities in GaAs and InP grown by various techniques will clearly be important to the further application of these materials.

Historically, most of the conclusions regarding the identity of the residual acceptors and donors in GaAs and InP that have been inferred by non-spectroscopic means, such as analysis of the growth environment or comparisons with other materials, have later been found to be incorrect. Spectroscopic analysis is therefore vital for the reliable identification of the impurities that are unintentionally introduced by various growth techniques. Even spectroscopic methods must be very carefully applied and interpreted to yield valid results. Variable-temperature Hall effect measurements can provide estimates of the thermal ionization energies of the donors in n-type material or the acceptors in p-type material. However, these estimates cannot be used to reliably identify different shallow donor and acceptor species in GaAs and InP, where the variations in thermal ionization energies as a function of doping level often exceed the minute differences in ionization energies among various species (known as "central-cell corrections"), particularly for donors.⁵ Hall effect measurements are also of no value in identifying minority impurity species. The principal utility of Hall effect data is in establishing quantitative values of total N_D and N_A , which can be obtained fairly accurately with that technique.⁵ Photothermal ionization spectroscopy⁶ is a very useful technique for the identification of donors in n-type material, and has also been applied to the study of acceptors in p-type GaAs.⁷ However, like Hall effect measurements, it is of no use in studying minority species in GaAs or InP.

Low temperature photoluminescence (PL) is probably the simplest and most useful technique which is available for the qualitative analysis of residual impurities in GaAs and InP. Both donors and acceptors can be chemically identified, and the relative concentrations of the various species can be estimated from the PL spectra in either n- or p-type samples. The sensitivity of the method is extremely high. For example, under

favorable conditions, concentrations of individual acceptor species as low as 10^{11} cm^{-3} can be detected, a level which is much lower than the capabilities of conventional chemical analysis techniques such as secondary ion mass spectroscopy (SIMS). Moreover, the method is completely non-destructive and does not require electrical contacts to the sample. No sample preparation is required, and very small or irregularly shaped samples can be utilized. A high degree of lateral spatial resolution is possible using focused excitation, and useful depth profiling can be performed either by varying the wavelength (and hence absorption coefficient) of the exciting light or by successive etching.

Other advantages of the PL technique include the good signal-to-noise ratio which is typically attainable in the spectra of direct-gap materials, and the rapidity of the measurement. A single spectrum can be recorded in a matter of minutes (after cooling the samples) and a thorough analysis under various measurement conditions takes only ~ 2 -3 hours. Data analysis is performed quite rapidly in most cases. The main limitations of the method are its requirements on sample purity ($n \leq 10^{15} \text{ cm}^{-3}$ for n-type and $p \leq 10^{16}$ for p-type material are required to identify acceptors using non-selective excitation in GaAs⁸), the inability to study non-radiative centers, and the complexity of the spectra.

In this work, the PL process has been reviewed from a fundamental point of view and then applied to the identification of residual acceptors in material grown by various techniques under various growth conditions. Since the identification of donors in GaAs or InP by PL requires extremely high resolution and/or high magnetic fields,⁹⁻¹¹ neither of which were available for this study, we relied exclusively on photothermal ionization data on the same samples to provide information on the donors. Bulk GaAs of sufficient purity was not available, so the investigation was confined to epitaxial GaAs and to preliminary measurements on epitaxial InP and a few high purity bulk InP crystals.

2. ANALYSIS OF PL SPECTRA

The process of low temperature photoluminescence may be described very briefly as follows. The excitation light is chosen (for the case which will be considered here) to have a photon energy larger than the band gap of the material. This light is therefore strongly absorbed near the front surface of the sample. The photoexcited electron-hole pairs rapidly thermalize by phonon emission, and diffuse into the sample via an ambipolar diffusion mechanism. The details of this process are discussed by Bebb and Williams.¹² Recombination of the excess carriers takes place through an enormous variety of radiative and non-radiative channels. The resulting spectrum of the luminescence which manages to escape back through the front surface of the sample is therefore highly complex, particularly for high purity material where spectral broadening effects are minimized.

The first essential step in analyzing any PL spectrum is therefore to identify the physical nature of the recombination processes which are responsible for each of the observed spectral features. Such identifications typically depend on studying the behavior of the PL peaks as a function of sample parameters, such as donor and acceptor concentrations, and as a function of measurement conditions, such as temperature, excitation intensity, excitation wavelength (i.e., resonant absorption effects), applied uniaxial stress or hydrostatic pressure, external electric or magnetic fields, and time-dependent luminescence measurements. The main parameters that were employed in the present study were sample purity, temperature, excitation intensity, and weak electric fields.

Once the recombination processes have been elucidated, the second step in the analysis is to determine the chemical and/or metallurgical nature of the defects and impurities which participate in these recombination processes. Indeed, most of the luminescence which is observed at low temperature is extrinsic in origin. The identity of native defects is in general quite difficult to determine, and can usually be surmised only from very indirect evidence such as controlled annealing experiments. Defects can be

intentionally created in a sample, for example, by bombardment with energetic particles, but the exact nature of the defects thus introduced is frequently unclear. Moreover, the reduction in luminescence efficiency that results from the non-radiative levels which are introduced may make PL characterization rather difficult in such material. Identification of impurity levels is in principle rather more straightforward, involving deliberate back-doping of high purity material with low levels of specific impurities. Such intentional doping experiments are often quite exacting, however, owing to the very low concentrations of impurities which must be introduced.

The characteristic defects and impurities of each growth technique can thus be determined, and controlled experiments can potentially provide information on the source of each impurity in the growth environment and the impurity incorporation mechanisms. Techniques to minimize the incorporation of defects and impurities can then be developed.

The research performed under this contract has focused on each of the three areas described above. Results on the incorporation of amphoteric impurities in LPE, AsCl_3 -VPE, AsH_3 -VPE, MOCVD, and MBE epitaxial GaAs obtained in this research are summarized below.

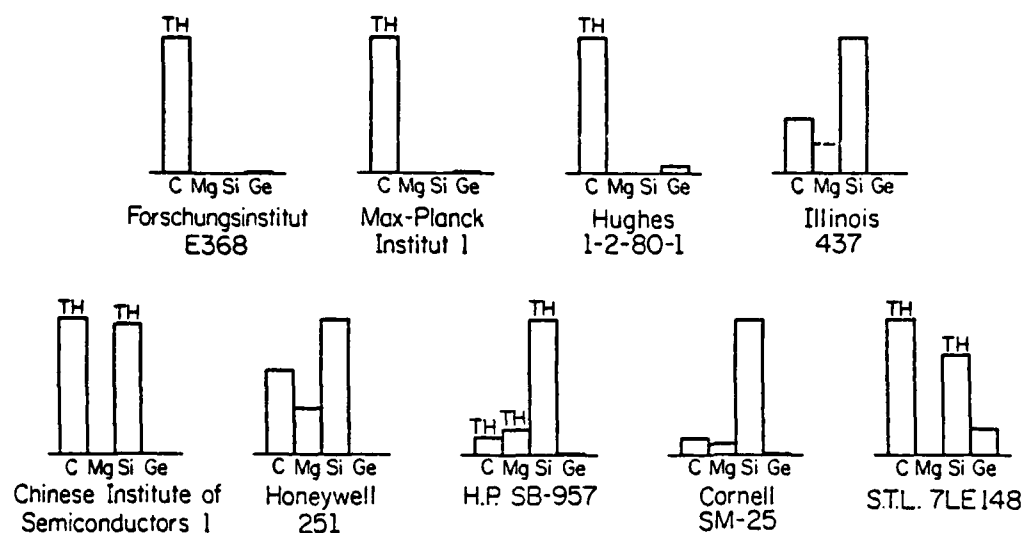
2.1 Amphoteric Impurities in LPE

The residual donors were identified in several of the samples discussed here using photothermal ionization spectroscopy; the spectra have been presented elsewhere.¹³ A qualitative measure of the relative donor concentrations in those samples can be obtained from the relative heights of the various donor peaks. In many cases the relative peak heights do not give an accurate indication of the quantitative relative concentrations due to the effects of absorbance saturation in the photothermal ionization spectra of these samples.¹⁴ In particular, the concentration of the dominant residual donor species in several cases is probably considerably under-estimated, relative to the concentrations of the other donors.

It is seen from Fig. 1(b) that S is the dominant residual donor in all of the samples. This is true whether the samples were grown in graphite or fused silica boats. Small quantities of Si donors are observed in 4 of the 7 samples; Si acceptors are present in substantial quantities in those 4 samples as seen from Fig. 1(a). The identity of the other 2 donor species observed is not entirely clear. The "Pb" peak is probably due to Te. This is rather likely considering the extremely low distribution coefficient of Pb in GaAs.¹⁵ The "Sn" donors could instead, be Se, since these 2 donor species have nearly identical ionization energies (see Ref. 16 and references therein). In the Cornell sample, the observation of Sn acceptors makes the presence of Sn donors extremely likely, but no definite statement can be made about the other samples. No Ge donors are observed in any of the LPE samples, even when trace quantities of Ge acceptors are observed.

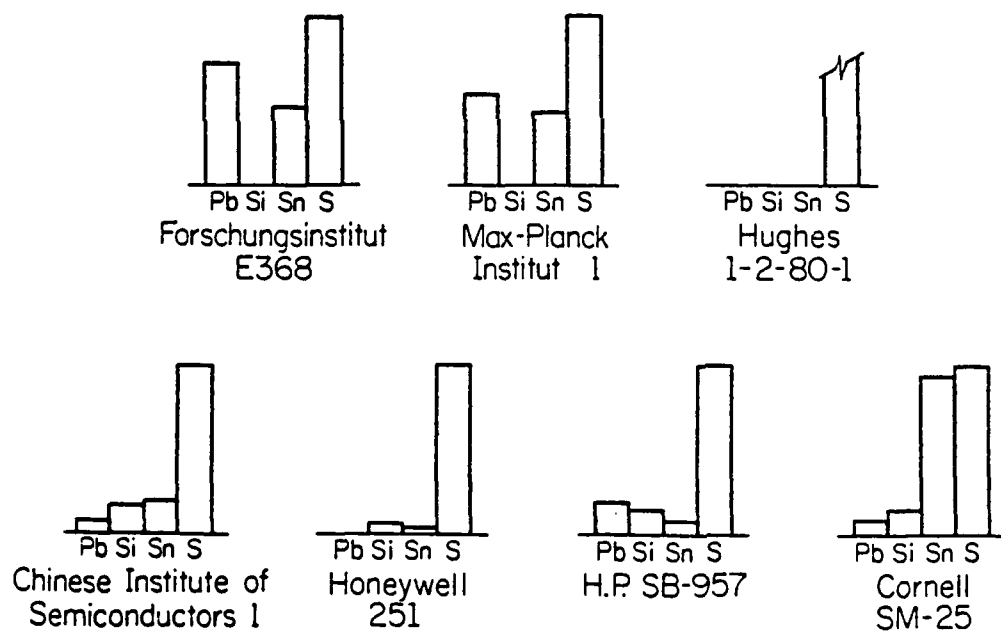
It is of interest to compare these results to those of previous studies. While oxygen has been proposed a number of times as the dominant shallow donor species in LPE GaAs (see e.g., Refs. 17-19), no spectroscopic evidence for this contention has ever been presented and it clearly contradicts the present results. Similar remarks can be made concerning early speculation that C was the dominant donor.²⁰ Kang and Greene correctly hypothesized that S might be the dominant donor, based on the temperature dependence of the residual doping and the presence of 0.2 ppm of S in the graphite crucible used for growth, but no direct evidence was obtained.²¹ The only previous spectroscopic studies concluded that Si was the dominant donor in samples grown in both graphite²² and fused silica²³ boats, with lower levels of Pb and Sn present although the latter identifications were not considered definite. These previous studies are consistent with the results presented here if more recent donor identifications are applied to those data.¹³ (The donor peak previously thought to be Si is now known to be S).

The previous photoluminescence study of Ashen *et al.*⁸ identified C and Si as the dominant acceptors in LPE samples grown in either fused silica or graphite boats, with traces of Ge also frequently seen.⁸ Zschauer found the dominant PL acceptor peaks for



(a) Relative Concentrations of Shallow Acceptors
in LPE GaAs Samples

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(b) Relative Concentrations of Shallow Donors
in LPE GaAs Samples

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Fig.1 Residual impurities in the LPE samples grown in various laboratories. a) Residual acceptors. b) Residual donors.

samples grown in vacuum in various types of boats to be those now known to be due to C.²⁴ The PL results are largely in accord with previous studies, but the observation of significant levels of Mg in 4 samples is interesting given that residual Mg acceptors have never previously been reported in LPE material.

Correlations of the residual acceptor and donor species in the same LPE samples have not previously been performed. A comparison of Figs. 1(a) and 1(b) indicates that the residual Si incorporates predominantly as acceptors in these samples, which were all grown at temperatures $\ll 860^\circ\text{C}$, the temperature below which Si acts as a p-type dopant in LPE.²⁵ This result is in agreement with values of the compensation ratio deduced from electrical measurements on intentionally Si-doped samples,²⁵ and with theoretical analysis of its behavior in LPE by Teramoto.²⁶ The residual Ge exhibits similar behavior in accord with its well known behavior as a p-type dopant.²⁶ On the other hand, Sn acceptors are found only in the sample with the largest concentration of Sn donors (Cornell). Doping experiments with Sn produced similar conclusions based on electrical measurements.²¹ The n-type behavior of Sn under Ga-rich growth conditions can be understood on the basis of its covalent radius.²⁶ Apparently C incorporates exclusively as an acceptor in GaAs, which has been explained theoretically²⁷ using arguments along the lines of Teramoto's theory for Si, Ge, and Sn.²⁶

2.2 Amphoteric Impurities in AsCl₃-VPE

The residual donors were identified in 23 of the 58 AsCl₃-VPE samples studied, using photothermal ionization spectroscopy.²⁷ Since the spectra of most of these samples are severely affected by absorbance saturation and related effects,¹⁴ it is not possible to give a quantitative analysis of relative donor concentrations in those samples. However, it is possible to state that Si is by far the dominant donor species in virtually 100% of the undoped samples grown by the conventional (Ga-AsCl₃-H₂) technique. All of the samples also exhibit smaller amounts of S donors, 87% show low levels of Ge donors, and Se or Sn donors (which cannot be distinguished) are detected at low concentrations in about 26%

of the samples. Only in about 35% of the samples is Ge present at greater than "trace" concentrations. It may be that Se or Sn is present at low levels in many more of the samples than are identified as containing one of those donors, since a large Si peak can easily obscure a smaller peak due to Se or Sn.

If Sn is in fact present in some of these samples, then it incorporates predominantly as a donor, since Sn acceptors are never detected in any of the VPE samples. Carbon incorporates exclusively as an acceptor is apparently the case in GaAs for all epitaxial growth techniques. Since Si acceptors typically constitute only a few percent of N_A , and Si donors typically account for most of N_D , we find that Si exhibits a strong preference for the Ga site in VPE material (which is opposite to its behavior in LPE). In those samples where Ge donors are undetectable or only present at "trace" levels, Ge acceptors are typically undetectable; in those samples having a "significant" concentration of Ge donors, Ge acceptors typically constitute about 9% of N_A . Because of absorbance saturation effects in the donor spectra, quantitative analysis of the amphoteric behavior of Ge in these VPE GaAs samples is not possible, but Ge clearly shows a preference for the Ga site, though not so strongly as for Si.

The behavior of the residual column IV elements discussed above is consistent with the behavior of those elements as intentional dopants in VPE.^{28,29} Their behavior is also consistent with the theoretical predictions of Ashen *et al.*,⁸ who on the basis of an extension of Teramoto's calculation for impurities in LPE²⁶ predict a ratio of $[Si_{Ga}] / [Si_{As}] = 1.6 \times 10^3$ for $T_G = 750^\circ C$ and $P(AsCl_3) = 6 \times 10^{-3}$ atm. In analogy with Ashen *et al.*, Low *et al.* predict corresponding ratios of $[Ge_{Ga}] / [Ge_{As}] = 3.7 \times 10^2$, $[Sn_{Ga}] / [Sn_{As}] = 3.9 \times 10^4$, and $[C_{Ga}] / [C_{As}] = 1.2 \times 10^{-2}$ under the same conditions.²⁷ These calculations explain the progressively greater n-type behavior of Ge, Si, and Sn (in that order) and the p-type behavior of C, although the quantitative accuracy of the calculations is probably not very good. In particular, the calculated values for $[Si_{Ga}] / [Si_{As}]$ and $[Ge_{Ga}] / [Ge_{As}]$ seem substantially too large, since if they were correct, we would not be able to observe $[Si_{As}]$

and $[\text{Ge}_{\text{Ga}}]$ at all. Qualitatively, the stronger preference of the amphoteric impurities for the Ga site in VPE as compared to LPE is simply due to the larger value of the As activity in the former growth environment,⁸ which leads to a larger Ga vacancy concentration in the solid and hence enhanced incorporation of impurities on the Ga sites.²⁶

2.3 Amphoteric Impurities in AsH_3 -VPE

The residual donors were studied by photothermal ionization spectroscopy in 30 AsH_3 -VPE samples. Some of the spectra have been presented elsewhere.^{30,31} In the samples grown at Hanscom AFB and Honeywell, the dominant donor is S in all cases, with much lower levels of Si and Ge also present. This observation is very different from the AsCl_3 -VPE system, where Si donors predominate; the difference in Si content could result from differences in the equilibrium partial pressure of HCl in the 2 systems, which affects the incorporation of Si from chlorosilanes. The origin of the S in either the AsCl_3 or AsH_3 -VPE systems is not yet clear, so no comments can be made regarding its dominance in the AsH_3 -VPE samples.

In the AsH_3 -VPE samples grown in our laboratory, S was the dominant donor in a majority of cases, but much more significant levels of Si and Ge donors are also observed and one or the other of these is sometimes the dominant donor. The relative importance of Si as compared to Ge is found to depend strongly on the partial pressure of AsH_3 , as will be discussed in the following section.

In general, the trends that are observed in the incorporation of Si and Ge donors are reflected in the concentrations of Si and Ge acceptors observed in the PL spectra. Both of these elements are found to exhibit a strong preference for the Ga site in the AsH_3 -VPE system (similarly to the case of AsCl_3 -VPE). In particular, $[\text{Ge}_{\text{As}}]$ constitutes at most 5% of N_{A} even in n-type samples where $[\text{Ge}_{\text{Ga}}]$ constitutes the vast majority of N_{D} ; similarly $[\text{Si}_{\text{As}}]$ is at most 1% of N_{A} when $[\text{Si}_{\text{Ga}}]$ dominates N_{D} . Furthermore, $[\text{Ge}_{\text{As}}]$ exceeds $[\text{Si}_{\text{As}}]$ even when $[\text{Si}_{\text{Ga}}]$ is equal to or even exceeds $[\text{Ge}_{\text{Ga}}]$ by a significant factor. It is therefore apparent that residual Ge is more strongly amphoteric than residual Si in AsH_3 -

VPE. This conclusion is similar to those for LPE GaAs which is intentionally doped with Si or Ge²⁶ or for AsCl₃-VPE material (see above).

The differences in Si and Ge acceptor backgrounds between the Hanscom AFB and Honeywell samples and the samples from our laboratory are readily understood in terms of the differences in Si and Ge donor backgrounds. The samples from the former 2 laboratories have relatively small [Si_{Ga}] and [Ge_{Ga}], so that Si_{As} and Ge_{As} are usually undetectable. The Illinois samples typically have larger [Si_{Ga}] and [Ge_{Ga}], so that Si_{As} and particularly Ge_{As} are more frequently seen. The differences in overall Si and Ge content among the samples from the various laboratories are not fully understood, but may relate to different growth conditions, source materials, reactor designs, etc.

2.4 Amphoteric impurities in MOCVD

The residual donors were identified in 22 of the MOCVD samples studied, using photothermal ionization spectroscopy; some of these data has been presented elsewhere, ^{27,32,33,34} as has some of the PL data described here.^{27,34} In nearly all of the samples that have been characterized, Ge is by far the dominant residual donor species. In 2 samples grown from a very impure TMG source, Sn is the dominant donor, but these are the only exceptions. Other donors such as Te, Si, Se or Sn, and S are observed in a number of samples, but usually in relatively minor quantities.

The typical [AsH₃] / [TMG] ratios employed in MOCVD growth at atmospheric pressure are on the order of 10-20 or even substantially higher. The As activity in the growth ambient is therefore even higher than in AsCl₃-VPE or AsH₃-VPE, where the As/Ga ratio is usually closer to unity. One might therefore expect the column IV elements such as Si, Ge, and Sn to preferentially occupy Ga sites even more strongly than in other VPE systems (C will still prefer the Ga site owing to its very small size).

This prediction is confirmed by a comparison of the photothermal ionization and PL data, since Ge acceptors are present at only trace levels ($\sim 10^{12} \text{ cm}^{-3}$ or below) when Ge donors occur at concentrations on the order of 10^{15} cm^{-3} . Since Si is less amphoteric (i.e.,

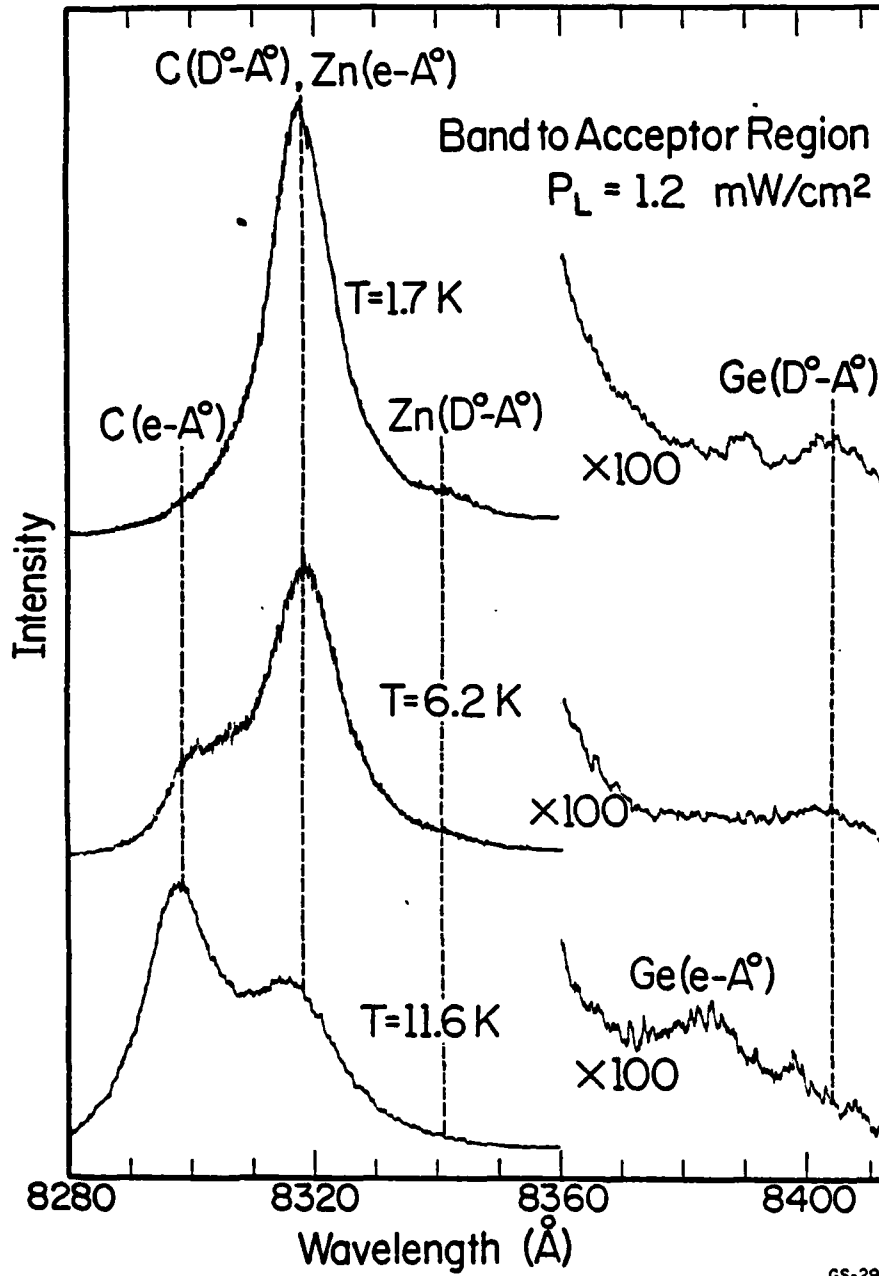
incorporates to a larger extent as a donor) than Ge in other growth techniques, and since the Si donor concentration in these MOCVD samples is always much less than that of Ge, it is not at all surprising that Si acceptors are never observed as a residual impurity in MOCVD. Similarly, the lack of any Sn acceptors in the samples where Sn is the dominant donor is not surprising.

The observation of Ge acceptors (even at trace levels) in some of these samples helps to confirm the identity of the dominant residual donor peak as Ge (the identity of this donor peak was at one time uncertain¹⁵). A set of spectra for a relatively impure sample containing traces of Ge acceptors is shown in Fig. 2, to illustrate the presence of Ge acceptors. Correlations between Ge acceptor and donor concentrations as a function of growth conditions are discussed below.

2.5 Amphoteric Impurities in MBE

The behavior of the amphoteric elements Si, Ge and Sn as a function of As₂/Ga ratio in AsH₃-MBE is discussed above. In the case of solid As-source MBE material, the $[Si_{As}] / [Si_{Ga}]$ ratio is also found to depend on the As/Ga ratio, and on the substrate temperature. In the series of samples grown at Bell Laboratories, Si acceptors are undetectable in most of the samples (Figs. 3 and Fig. 4). However, the sample grown at the highest temperature (650°C, As/Ga = 15) shows evidence of small amounts of Si acceptors. The spectrum of the latter sample is shown in Fig. 5 and exhibits a small Si (D°-A°) peak on a 10x expanded scale. High temperatures and low As fluxes both tend to enhance the As vacancy concentration and increase the incorporation of impurities into As sites. Similar, though somewhat more pronounced effects have been reported elsewhere.³⁵

In all cases we find that Si incorporates primarily as a donor in MBE, at least on (100) substrates using reasonably "normal" As-stabilized growth conditions. We find that $[Si_{As}]$ is usually negligible compared to $[C_{As}]$ or $[Si_{Ga}]$, in agreement with recent findings by Nottenburg *et al.*³⁶ The behavior of Si in MBE is not surprising given that growth with



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Fig. 2 PL spectra of the (D°-A°) and (e-A°) peaks in a relatively impure MOCVD sample grown at Rockwell ($n_{77} = 2.6 \times 10^{15} \text{ cm}^{-3}$, $\mu_{77} = 42,000 \text{ cm}^2/\text{Vs}$) at low excitation and 3 different temperatures.

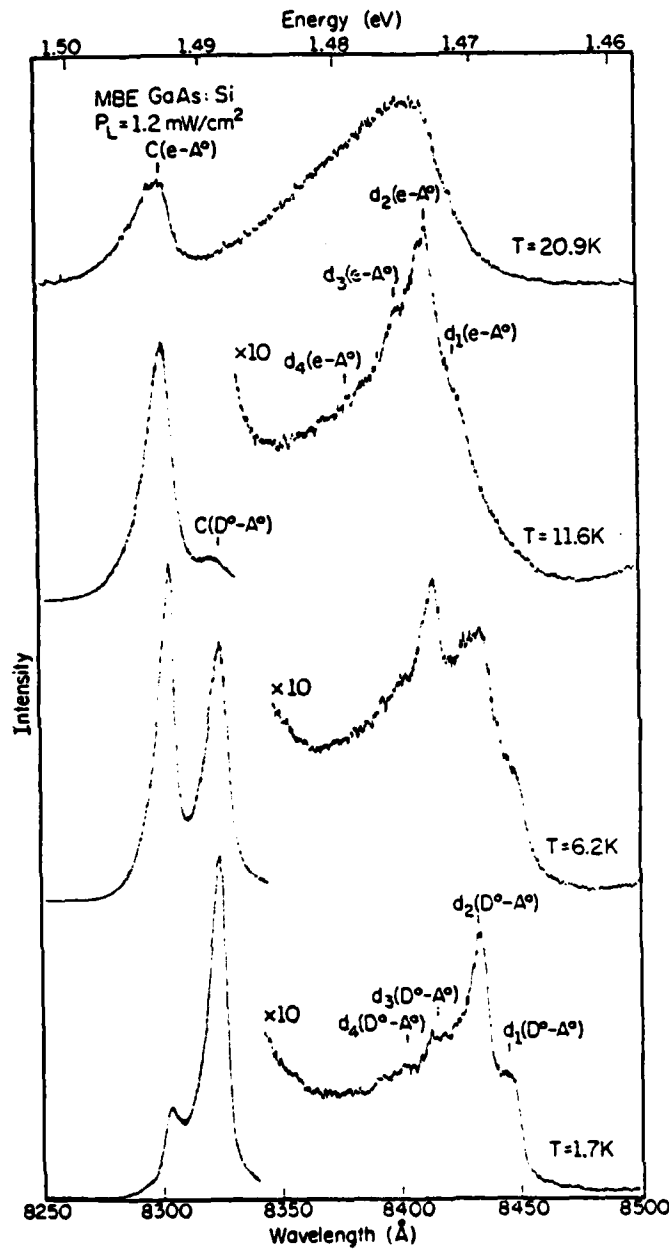


Fig. 3 The $(D^\circ-A^\circ)$ and $(e-A^\circ)$ transitions in the PL spectrum of a high purity Si-doped MBE sample grown by J.C.M. Hwang at Bell Laboratories (high resistivity, electrically unmeasurable), shown at a low excitation level and 4 different temperatures. The higher energy peaks are due to C acceptors while the lower energy peaks d_1-d_4 (shown on an expanded scale) are due to defects or complexes.

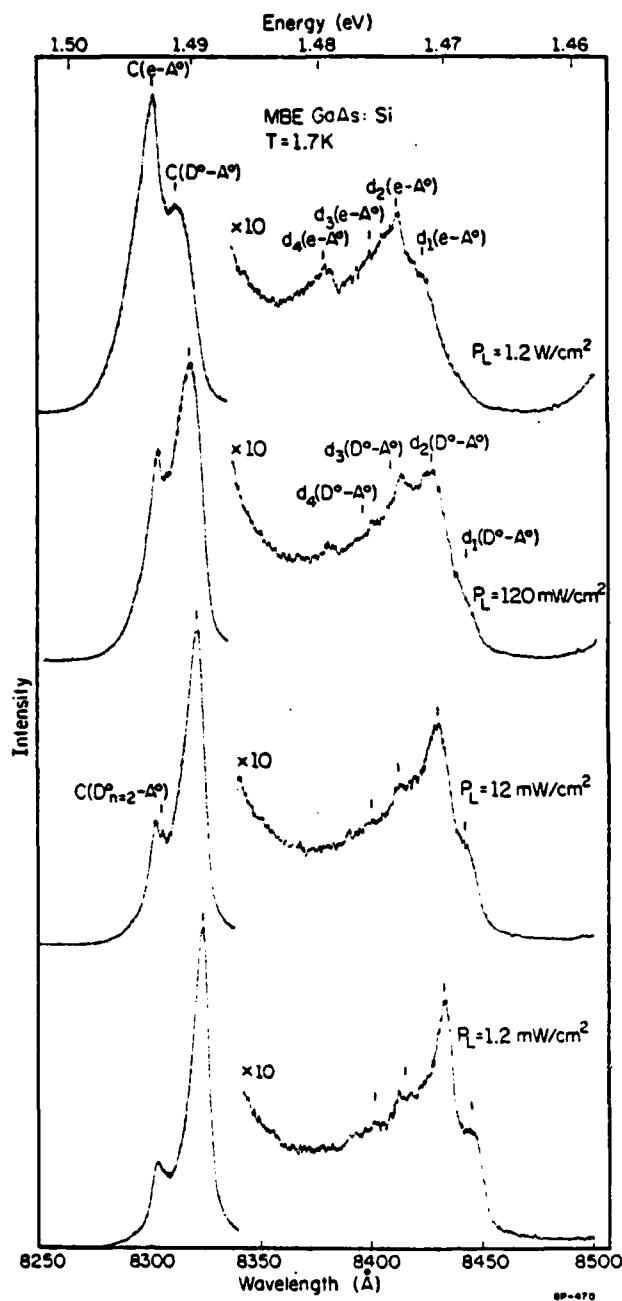


Fig. 4 $(D^{\circ}-A^{\circ})$ and $(e-A^{\circ})$ peaks due to C and the d_1 - d_4 acceptor levels in the PL spectrum of the sample of Fig. 3.11, recorded at low temperature (1.7 K) and at 4 different excitation levels.

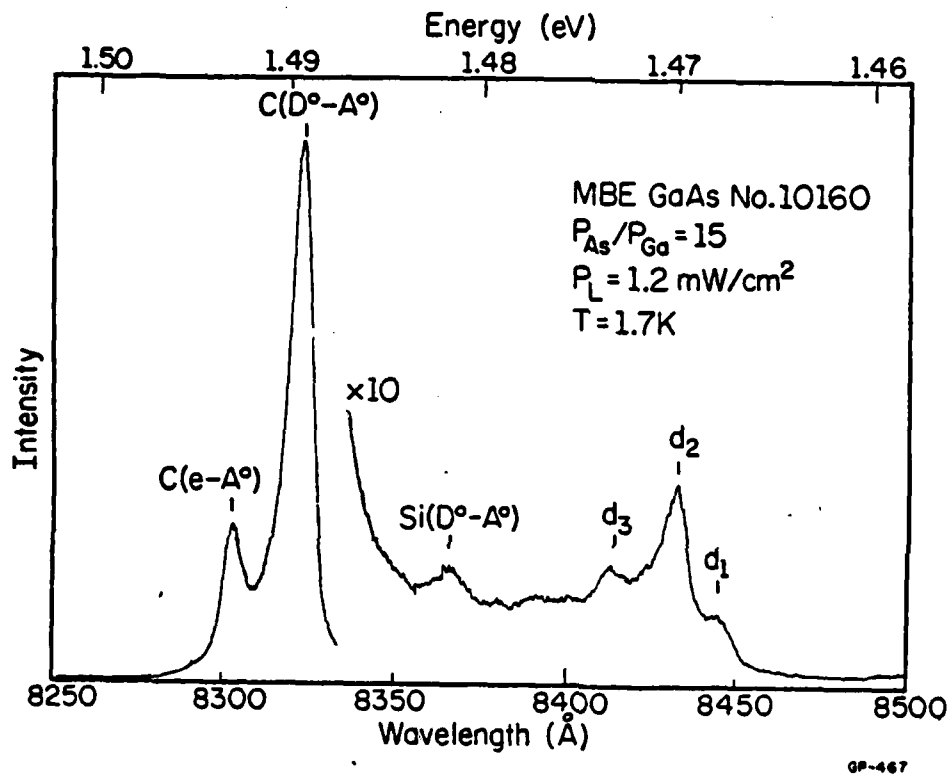


Fig. 5 A PL spectrum of a MBE sample grown at Bell Laboratories at a low As/Ga flux ratio ($n_{77} = 1.97 \times 10^{14} \text{ cm}^{-3}$, $\mu_{77} = 126,000 \text{ cm}^2/\text{Vs}$).

an As-stabilized surface, i.e., an excess of As, corresponds to a high As activity in the growth ambient and therefore favors incorporation of impurities into Ga sites.

We do not have sufficient data to quantitatively analyze the behavior of Ge in MBE, but it is definitely more amphoteric than Si (as is also observed in other growth techniques) from a comparison of the PL and photothermal ionization spectra. It may even behave primarily as an acceptor as it apparently does for the Ge-doped (p-type) sample that we measured. Similar behavior is reported elsewhere for Ge-doped MBE material.³⁷

3. COUPLING ACTIVITIES

In the course of this work, we have collaborated with crystal growers from many different laboratories around the world in the characterization of high purity GaAs grown by the different techniques. The table below lists the crystal growers who have contributed samples to this work and indicates the research organization with which they are affiliated.

Sources of High Purity LPE GaAs

J. K. Abrokwah	Honeywell Technology Center
E. Bauser	Max Plank Institute, Stuttgart
G. E. Bulman	University of Illinois
L. F. Eastman	Cornell University
P. D. Green	Standard Telecomm. Laboratories
D. E. Holms	Hughes Research Laboratories, Malibu
C. E. Stolte	Hewlett Packard Laboratories
E. Kuphal	Forschungsinstitut-der DBP beim FTZ FDR
X. R. Xhong	Institute of Semiconductors, Beijing

Sources of High Purity VPE GaAs

AsCl₃ VPE

C. O. Bosler	M.I.T. Lincoln Laboratory
T. H. Miers	Motorola Incorporated
G. L. McCoy	Wright-Patterson Air Force Base
A. Shibatomi	Fujitsu Laboratories
C. M. Wolfe	Washington University
P. Colter	University Energy Systems
X. R. Xhong	Institute of Semiconductors, Beijing
K. Arai	NEC Corporation

AsH₃ VPE

J. K. Abrokwhah
 J. K. Kennedy
 T. J. Roth
 R. Sankaran
 A. Usui

Honeywell Technology Center
 Hanscom Air Force Base
 University of Illinois
 Avantek
 NEC Research Laboratories

Sources of High Purity MOCVD GaAs

P. D. Dapkus, K. L. Hess
 T. Nakanisi, T. Udagawa
 R. Bhat
 L. F. Eastman, J. R. Shealy
 J. J. Coleman
 M. Feng
 P. E. Norris
 T. Maeda
 F. T. J. Smith
 K. A. Jones
 S. D. Hersee
 K. M. Lau
 J. Auclair

Rockwell International
 Toshiba Corporation
 Bell Laboratories, Murray Hill
 Cornell University
 University of Illinois
 Ford Microelectronics
 General Telephone and Electronics
 Sumitomo Chemical Company
 Kodak Research Laboratories
 University of Massachusetts, Amherst
 Thomson - CSF
 University of Massachusetts, Amherst
 OMVPE Technologies Inc.

Sources of High Purity MBE GaAs

A. R. Calawa
 D. M. Collins
 J. C. M. Hwang
 H. Morkoç
 A. Y. Cho
 C. E. C. Wood, L. F. Eastman
 S. Palmateer
 M. Heiblum, W. I. Wang
 D. Miller
 E. Caine
 K. Arai
 J. S. Harris, E. C. Larkins

M.I.T. Lincoln Laboratory
 Hewlett Packard Laboratories
 Bell Laboratories, Murray Hill
 University of Illinois
 Bell Laboratories, Murray Hill
 Cornell University
 General Electric, Syracuse
 IBM
 Rockwell International
 University of California, Santa Barbara
 NEC Corporation
 Stanford University

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